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廈門大學

## 博 士 学 位 论 文

# 硫对砷胁迫下桐花树幼苗生理生态特征的影响

Effects of Sulfur on Eco-Physiological Characteristics of  
*Aegiceras corniculatum* L. Seedling under Arsenic Stress

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## 摘要

砷(Arsenic, As)是一种有毒并致畸致癌的化学元素,是海洋环境监测的重要指标之一。红树林为生长在热带、亚热带海岸潮间带的木本植物群落,在维持生态平衡和保护环境方面起着重要的作用。同时红树林湿地沉积物具有高硫(Sulfur, S)含量的特点,硫在植物生长以及解毒、防卫、抗逆等过程中起着重要的作用。目前关于红树林生态系统砷污染以及硫在红树植物抗 As 胁迫中的作用方面的研究鲜见报道。本研究采取 2 因素 4 水平全面设计栽培实验对桐花树(*Aegiceras corniculatum* (L.) Blanco)幼苗对 As、S 及其交互作用的生理学应答进行了研究,包括桐花树幼苗的生长情况(叶绿素含量、生物量),植株体内中硫、砷分布、砷形态分布(As(V)、As(III))及根表铁膜含量,植株体内有机渗透调节物质(可溶性糖、可溶性蛋白、有机酸)含量和含巯基化合物(非蛋白巯基 NPT、谷胱甘肽 GSH 和植物络合素 PCs)含量等,试图揭示硫对砷胁迫下桐花树幼苗生长和生理响应机制的影响。本研究得到主要结论如下:

1. 环境中过量的重金属会限制植物的正常生长与发育,红树植物在长期生长进化过程中对重金属污染演化出一套具有较强的耐受能力的策略,保证其种群在不利环境中能够顺利繁衍。本研究中,桐花树幼苗叶绿素含量和生物量之间对砷、硫复合处理下的响应并无显著相关。砷单一胁迫下,低浓度砷胁迫促进桐花树幼苗的生长,高浓度砷胁迫则抑制植株的生长,这与植物应对其它重金属胁迫的响应相似。在未施砷土壤中施硫能显著提高了桐花树幼苗的生物量( $p<0.05$ ),而在砷污染的土壤中施硫增加了植株叶绿素的含量却降低了植株的生物量,砷处理浓度与桐花树幼苗的生物量之间存在着极显著负相关关系( $p<0.01$ ),说明硫的施入能缓解砷对植株光合作用的毒害,但硫的施入可能使植株光合作用更多作用于缓解砷的毒害方面。

2. 砷单独胁迫抑制了桐花树幼苗对硫的吸收( $p<0.05$ ),而植株叶部硫含量在低浓度砷(As 30、As 60)处理下存在一定的上升说明植株加强对硫的转运,叶部硫含量趋势表明在砷胁迫下,植株加强硫在叶部的积累。在砷、硫复合处理中,植株加强了对土壤中硫的吸收和转运,根、叶部硫含量均有显著上升( $p<0.05$ ),其中低浓度硫处理相较于不含硫处理和高浓度硫处理能更有效地增加植株叶部硫的积累,硫在植株体内的积累可能是其抵御砷毒害的重要机制。在

低浓度砷（As 30、As 60）处理下，硫的施入促进根部对硫的吸收且将其转运到叶部；但在高浓度砷（As 150）处理下，桐花树幼苗体内的硫转运机制出现了抑制。硫是植物所需大量元素之一，硫对植物抵抗砷毒害，维持植物正常的生长和生理有着非常重要的作用。

3. 砷不是植物必需的元素，但是植物可以通过根系在其生长过程中从外界环境吸收砷。砷单独处理下，桐花树幼苗根、叶部的砷含量呈现出随砷处理浓度升高出现上升的趋势，根、叶部砷含量分别与砷处理浓度呈极显著正相关（ $r=0.938$ ,  $p<0.01$ ）和显著正相关（ $r=0.608$ ,  $p<0.05$ ）。这说明桐花树幼苗具有一定砷耐受性，其根部能吸收土壤中的砷且转运至叶部。桐花树幼苗对砷的积累主要在根部，桐花树幼苗叶部砷含量要极显著低于根部砷含量（ $p<0.01$ ）。砷、硫的复合处理中，硫能促进植株根部对砷的吸收并转运至叶部，低浓度硫处理下植株体内的砷含量较对照组（As 0-S 0）和未施硫组均有显著的升高（ $p<0.05$ ），表明在砷污染的土壤中施硫能促进植株对砷的吸收和转运，其具有一定的土壤砷污染修复效果。

4. 砷的毒性大小与其赋存形态有关，不同形态的砷化合物可以相互转化，通常来说无机砷的毒性高于有机砷，其中以无机砷 As(III)、As(V)的毒性最强。在本研究中，在桐花树幼苗体内检测到大量 As(III)，说明红树林土壤和植物能将实验施加的无机砷 As(V)形态转化成 As(III)形态。在砷污染的土壤中施硫能显著降低桐花树幼苗对两种毒性最强的无机砷 As(V)、As(III)的吸收，在同一砷浓度处理下，根部 As(V)、As(III)的含量随着硫处理浓度的升高而下降，施硫处理中含量极显著低于未施硫处理（ $p<0.01$ ）；植株叶部对这两种无机砷的积累也随着硫的施入而下降，其中低浓度砷处理下，施入硫使叶部的 As(III)含量未检出，说明硫的施入能降低植物对 As(V)、As(III)的吸收和转运，从而很大程度上降低砷对桐花树幼苗的毒害。

5. 红树植物适应厌氧环境的特征之一就是根系具有泌氧功能，根系的泌氧使得部分重金属在氧化条件下沉积于根际，并在根系表面形成根表铁氧化膜，根表铁膜能极大程度地吸附土壤中的砷从而减少植株对砷的吸收。砷单一处理下，桐花树幼苗根表铁膜含量在低浓度砷（As 30、As 60）处理中上升，表明根表铁膜的增加是其应对砷毒害的防御机制之一。桐花树幼苗根表铁膜含量与硫处理浓度

及植株根部的硫浓度均呈极显著正相关 ( $p<0.01$ )，说明硫的施入促进了植株的根表铁膜的合成，根部硫的积累有助于根部铁膜的合成。硫在根表铁膜的合成中发挥着重要的作用，在砷污染的土壤中施硫能显著增加砷胁迫下植株的根表铁膜含量，进而吸附土壤中的砷，降低植株对砷的吸收，减小砷对植株的毒害。

6. 有机渗透调节物质一方面作为渗透调节物质降低重金属对植物的危害，另一方面其也作为生理代谢物质维持着植物的正常生长。在本研究中，在砷污染的土壤中施入硫对有机渗透调节物质的含量有调节作用，但有机渗透调节物质与砷、硫处理浓度之间的相关性很难达到显著的水平，仅有叶部草酸的含量与硫浓度显著负相关 ( $p<0.05$ )。砷胁迫增加了桐花树幼苗根、叶中的可溶性糖、可溶性蛋白和有机酸等有机渗透物质的含量，其中根部的增加趋势要大于叶部，有机渗透调节物质主要作用是在调节根部的渗透压从而抑制植株对砷的吸收。在砷污染的土壤中施入硫显著降低了植株根部的可溶性糖、可溶性蛋白的含量 ( $p<0.05$ )，说明硫使植株对砷的解毒机制可能朝向其它通路而非有机渗透物质的调节。

7. 植物解除砷毒性的另一条重要途径就是合成富含巯基的多肽，如 GSH 和 PCs，这些多肽能与砷络合形成复合物，降低砷的毒性。在本研究中，砷单独胁迫下，低浓度砷处理使桐花树幼苗根、叶部中 NPT 包括 PCs 和 GSH 等巯基化合物的含量增加 ( $p<0.05$ )，表明巯基化合物在植株对砷的抗性中起着重要作用。而根部的 NPT、PCs 含量与砷处理浓度显著负相关 ( $p<0.05$ )，说明砷胁迫下植株加大了对 NPT、PCs 的消耗。硫处理浓度与叶部 NPT、根部 GSH 和叶部 PCs 含量呈显著正相关 ( $p<0.05$ )，说明硫的施入能显著地促进体内巯基化合物的合成。在砷污染的土壤中施入硫显著增加了植株体内巯基化合物含量（尤其是 PCs），PCs 作为 NPT 中最重要的重金属络合物质，其能络合砷形成无毒的化合物，从而缓解砷对植株的毒害。植株根、叶部 NPT 包括 PCs 和 GSH 等巯基化合物含量的高值均出现低浓度硫处理中，说明低浓度的硫对砷毒害的有着更好缓解作用。

**关键词：**桐花树；砷；硫；形态；巯基化合物

## Abstract

Arsenic (As) is a toxic and carcinogenic teratogenic chemical elements, that is one of the most important indicators of marine environmental monitoring. The mangrove wetland sediments with high Sulfur(S) features content, and sulfur play an important role in heavy metal tolerance mechanism. *Aegiceras corniculatum* (L.) Blanco is one of the main categories of sub-tropical coastal mangrove communities, and also one of China's major mangrove species. In the present study, we have taken two comprehensive design factor 4 level cultivation experiments sulfur, arsenic and their interactions on *A. corniculatum* seedling growth, in vivo the distribution of sulfur, arsenic, in vivo organic osmolytes and thiol-containing compound content. This study is try to explore sulfur of arsenic stress *A. corniculatum* seedling growth and physiological ecology. The main conclusions of this study are as follows:

Long-term growth of mangrove species in the evolutionary process evolved a set of heavy metal pollution has a strong tolerance policy plants to ensure that their populations can successfully reproduce the adverse environment. Low concentrations of arsenic have a promoting role in plant growth and development the while high concentrations of arsenic inhibited. In separate sulfur stress plant biomass was significantly increased. In sulfur, arsenic composite role, sulfur is applied into increased plant chlorophyll content was significantly reduced plant biomass, indicating that sulfur can effectively maintain the photosynthesis of plants under arsenic stress. The photosynthesis and biomass between pigment content on sulfur, arsenic the stress response was not significantly correlated. The apply of sulfur into the soil under arsenic stress may cause plant photosynthesis physiological and biochemical reactions toward mitigation arsenic on other pathways poisoned plants rather than increase plant biomass.

The content of sulfur, arsenic and the valence distribution of As(III) and As(V) and root iron plaque content were studied in order to explore the effect of sulfur on the in vivo distribution of arsenic and sulfur for *A. corniculatum* seedling under arsenic stress. Arsenic inhibited the sulfur absorption *A. corniculatum* seedlings. But

in arsenic, surfur composite role, plants enhance the soil absorption and transport of surfur, surfur accumulation in the plant body may be an important poison resist mechanism on arsenic. Arsenic accumulation mainly in the roots. In low concentrations arsenic, the plant can use a part of arsenic, the apply of surfur in arsenic contaminated soil can promote the uptake and translocation of arsenic in the plant, with some soil arsenic remediation effect.

In arsenic, surfur composite process, surfur significant reduced the total arsenic, As(V) and As(III) accumulation in *A. corniculatum* seedlings. Mangrove soils and plants can be effectively change As(V) into As(III). the apply of surfur is can significantly reduce the most toxic form of As(III) content into the plant body. In addition, the apply of surfur increase in the plant's iron plaque under arsenic stress, thus preventing the absorption of arsenic plants to increase plant resistance to arsenic.

Organic osmolytes in plant response to heavy metal stress the main means of response, which on the one hand to reduce the hazards of heavy metals on plants, on the other hand they also maintain normal growth of plants. arsenic stress can promote soluble sugar, soluble protein, and three total content of organic acids and other organic substances in *A. corniculatum* seedling root and leaf significantly, in which the roots have the greater increasing trend to leaf. The apply of surfur is applied into the can significantly alter the organic osmolytes response. Surfur can significantly reduce the organic osmolytes content of the palnt under arsenic stress, indicating that surfur may be from another mechanism reduces arsenic the plants hazards, maintain normal osmotic pressure in vivo plants.

Thiol compounds can be used as the specific biological markers plant response to of heavy metal pollution, they can form complex compands with arsenic and thereby reducing arsenic toxic effects on plants. In the present study, low concentrations of arsenic can effectively increase the content of NPT including GSH and PCs in *A. corniculatum* seedling roots, leaves, indicating that increasing the content of thiol compounds in *A. corniculatum* seedlings is an important stress response mechanism to arsenic. The apply of surfur significantly increased the thiol compound content in *A. corniculatum* seedlings in arsenic contaminated soil. Surfur can effectively alleviate

the thiol compound content in *A. corniculatum* seedling under arsenic stress, the effect of low concentrations of surfur is more significant .

**Keywords:** *Aegiceras corniculatum* (L.) Blanco; arsenic; surfur; chemical speciation; thiols

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